

# The $\delta$ Scuti star FG Vir. V. The 2002 photometric multisite campaign

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Received date; accepted date

**Abstract.** A high-accuracy multisite campaign was carried out from 2002 January to May with a photometric coverage of 398 hours at five observatories. The concentration on a few selected sites gives better consistency and accuracy than collecting smaller amounts from a larger number of sites. 23 frequencies were detected with a high statistical significance. 6 of these are new. The 17 frequencies found in common with the 1992–1995 data are the modes with highest amplitudes. This indicates that the pulsation spectrum of FG Vir is relatively stable over the ten-year period. Two frequencies have variable amplitudes and phases from year to year as well as during 2002. These were both found to be double modes with close frequencies. For the mode at 12.15 c/d this leads to an apparent modulation with a time scale of  $\sim 129$  d. The close frequencies at 12.15 c/d are composed of a radial and a nonradial mode, suggesting a similarity with the Blazhko Effect seen in RR Lyrae stars.

**Key words.** Stars: variables:  $\delta$  Sct – Stars: oscillations – Stars: individual: FG Vir – Techniques: photometric

## 1. Introduction

Asteroseismology of  $\delta$  Scuti stars has reached a stage where the choice between different models of stellar structure and evolution requires a large number of known pulsation frequencies. While the discovery of many new frequencies cannot be accompanied by successful pulsation mode identifications, the latter is important to refine the stellar pulsation models. So far, the observations could not yet be matched with perfect models due, in part, to lack of enough observational constraints.

Consequently, the Delta Scuti Network (DSN) specializes in the intensive study of a few selected pulsating stars. One of these objects is the star FG Vir, which was observed for several months during 2002. The motivation for additional photometry was:

(i) Successful mode identification relies on both photometric and spectroscopic techniques. While the first

method is used to determine the pulsational  $\ell$  values through phase differences and to a lesser extent, amplitude ratios, the line-profile technique allows accurate determinations of the  $m$  values and determines the rotational velocity as well as the aspect of the rotation axis,  $i$ . In 2002, for the first time the photometric campaign has been paired with an intensive multisite spectroscopic campaign.

(ii) A comparison of the photometric amplitudes with those obtained during previous campaigns from 1992–1995 would yield valuable information on the long-term stability of the pulsation spectrum.

(iii) Furthermore, a long campaign would lead to a high frequency resolution within the year of observation. This would permit the search for close frequency pairs, such as those that have been reported for several other  $\delta$  Scuti variables.

(iv) The mode selection mechanism operating in  $\delta$  Scuti stars is still unknown. Theoretical pulsation models predict considerably more modes than are observed. Consequently, it is important to study the stars in more detail to search for modes with small amplitudes and to increase the number of known frequencies.

The star FG Vir (= HD 106384) has been observed before: its variability was originally discovered by Eggen (1971) in one night of observation. During 1992, Mantegazza et al. (1994) measured FG Vir photometrically for 8 nights. They were able to identify six frequencies of pulsation, while a seventh mode of pulsation was also suggested. Two multisite photometric campaigns were organized by the Delta Scuti Network during 1993 (170 hours, Breger et al. 1995) and 1995 (435 hours, Breger et al. 1998). The multisite campaigns led to the discovery of 24 frequencies of pulsation, of which 21 were independent pulsation modes. A reasonable agreement between different attempts towards mode identifications was found (Guzik et al. 1998, Viskum et al. 1998, Breger et al. 1999, Mantegazza & Poretti 2002).

The Delta Scuti Network is engaged in a long-term study of FG Vir, using both photometric and spectroscopic techniques. Consequently, even larger and better analyses are expected in the future. These will include photometric frequency determinations, photometric and spectroscopic mode identifications as well as stellar modelling. The purpose of the present paper is to report the 2002 photometry and its implications for our understanding of FG Vir.

## 2. New measurements

A multisite photometric campaign of FG Vir was carried out from 2002 January to 2002 May. DSN campaigns strive for very long observing runs on relatively few telescopes located on different continents. This maximizes the observational stability and frequency resolution, while minimizing the negative effects of daily aliasing. The concentration on a few selected sites gives better consistency and accuracy than collecting smaller amounts from a larger number of sites. An analyses on the observational accuracy of global campaigns can be found in Breger (2002).

We consider the evolution of DSN campaigns to fewer sites and longer observations at each site to be an important step to produce homogeneous, high-quality data. Furthermore, data from all nights and telescopes with a photometric quality of less than 4 mmag per single observation (as judged from the comparison stars) are rejected. The journal of usable observations is given in Table 1.

The observations were obtained with standard photoelectric photometers, using photomultiplier tubes as detectors. All measurements were made through the Strömberg  $v$  and  $y$  filters to provide a relatively large baseline in wavelength. The three-star technique in which measurements of the variable star are alternated with those of two comparison stars, was adopted. Since the same photometric channel is used for all three measurements, the

procedure usually produces the required long-term stability of 3 mmag or better. We used the same comparison stars as during the 1993 and 1995 campaigns of FG Vir, viz., HD 106952 (F8V) and HD 105912 (F5V). Again, no variability of these comparison stars was found.

The following telescopes were used:

1. The APT measurements were obtained with the T6 0.75 m Vienna Automatic Photoelectric Telescope (APT), situated at Washington Camp in Arizona. The suitability of this telescope for campaigns requiring both photometric precision at the millimag level as well long-term stability was already tested and confirmed by Breger & Hiesberger (1999).
2. The OSN measurements were obtained with the 0.90 m telescope located at 2900m above sea level in the South-East of Spain at the Observatorio de Sierra Nevada in Granada, Spain. The telescope was equipped with the simultaneous four-channel photometer (*uvby* Stromgren photoelectric photometer). The observers were: P. Amado, V. Costa, R. Garrido, P. Lopez de Coca, S. Martin Ruiz; I. Olivares, E. Rodriguez, and A. Rolland.
3. The SAAO  $v$  and  $y$  measurements were made with the Modular Photometer attached to the 0.5 m telescope of the SAAO. The observers were F. Rodler and T. Tshenye. These  $v$  and  $y$  observations are of the highest quality with agreement between the comparison stars of  $\sim 2$  mmag. Additional measurements obtained with the 0.75 m telescope at SAAO by M. L. Pretorius and F. Rodler were slightly less accurate at the 4 mmag level in  $y$ , while all  $v$  measurements had to be rejected.
4. The SPM measurements were carried out with the 1.5 m telescope at the San Pedro Martir Observatory, Mexico. The 1.5 m telescope was equipped with a simultaneous *uvby* Stromgren photometer, which is the twin of the OSN instrument mentioned above. The observations from S. Pedro were planned at the end of the APT campaign in order to minimize overlaps and to significantly increase the time baseline of the whole DSN campaign. The organization of the measurements and the reductions were made by E. Poretti, and the observers were J. Pierre Sareyan and Manuel Alvarez. The analysis of the two comparison stars showed residuals of  $\pm 3.4$  millimag per single observations in the  $y$  filter, while  $v$  measurements were of poor quality ( $\pm 8.4$  mmag) due to instrumental problems. Consequently, only the (high-quality)  $y$  measurements were retained.
5. The MJ measurements supplemented the previous data by an additional night of  $y$  measurements obtained with the 0.6 m telescope at Mount John, New Zealand. The observer was P. Kilmartin.

## 3. Detection of the pulsation frequencies

The pulsation frequency analyses were performed with a package of computer programs with single-frequency

**Fig. 1.** Multisite photometry of FG Vir obtained during the 2002 DSN campaign.  $y$  and  $v$  are the observed magnitude differences (variable – comparison stars) normalized to zero in the narrowband  $uvby$  system. The fit of the 23-frequency solution derived in this paper is shown as a solid curve. Triangles: APT; filled diamonds: SAAO 0.5 m; filled circles: SAAO 0.75 m, open squares: OSN, diamonds with +: MJO, stars: SPM

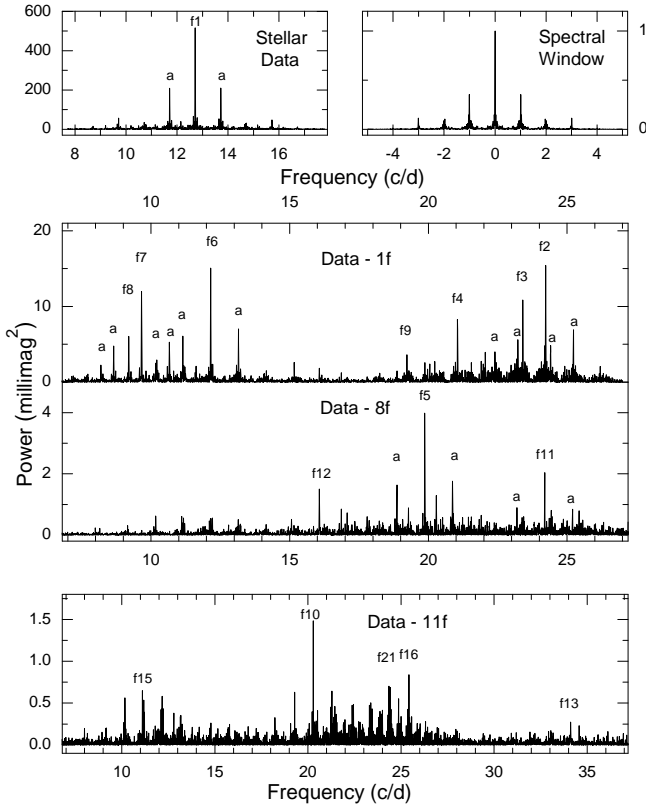
**Table 1.** Journal of the PMT observations of FG Vir

Start HJD (days)	Length (hours)	Observatory	Telescope	Start HJD (days)	Length (hours)	Observatory	Telescope
2452306.60	3.6	OSN	0.9m	2452355.45	6.0	OSN	0.9m
2452307.64	2.9	OSN	0.9m	2452356.46	5.6	OSN	0.9m
2452308.60	3.0	OSN	0.9m	2452356.71	1.8	APT	0.75m
2452310.67	1.1	OSN	0.9m	2452357.42	6.4	OSN	0.9m
2452313.82	4.5	APT	0.75m	2452357.85	1.8	APT	0.75m
2452314.55	4.8	OSN	0.9m	2452358.71	5.3	APT	0.75m
2452314.83	5.2	APT	0.75m	2452359.90	2.9	MJ	0.6m
2452315.82	4.5	APT	0.75m	2452360.34	5.2	SAAO	0.5m
2452316.53	5.3	OSN	0.9m	2452363.37	4.1	SAAO	0.5m
2452317.81	5.2	APT	0.75m	2452363.74	4.4	APT	0.75m
2452324.54	4.5	OSN	0.9m	2452364.34	5.4	SAAO	0.5m
2452325.57	4.0	OSN	0.9m	2452365.35	4.7	SAAO	0.5m
2452325.79	5.6	APT	0.75m	2452365.68	5.7	APT	0.75m
2452326.79	4.5	APT	0.75m	2452367.31	5.8	SAAO	0.75m
2452327.39	4.4	SAAO	0.75m	2452367.68	5.6	APT	0.75m
2452327.61	1.6	OSN	0.9m	2452368.24	5.5	SAAO	0.75m
2452328.55	4.6	OSN	0.9m	2452368.68	3.9	APT	0.75m
2452328.79	4.4	APT	0.75m	2452369.25	1.4	SAAO	0.75m
2452329.52	5.4	OSN	0.9m	2452370.35	4.8	SAAO	0.75m
2452330.54	5.1	OSN	0.9m	2452370.73	1.7	APT	0.75m
2452335.77	5.3	APT	0.75m	2452371.24	6.7	SAAO	0.75m
2452336.40	4.7	SAAO	0.75m	2452372.66	3.1	APT	0.75m
2452336.77	5.5	APT	0.75m	2452373.23	2.7	SAAO	0.75m
2452337.44	4.0	SAAO	0.75m	2452373.66	3.1	APT	0.75m
2452338.77	4.0	APT	0.75m	2452379.72	2.3	APT	0.75m
2452341.59	2.5	OSN	0.9m	2452380.45	3.7	OSN	0.9m
2452342.48	3.5	SAAO	0.5m	2452380.75	3.0	APT	0.75m
2452342.74	5.7	APT	0.75m	2452381.34	6.0	OSN	0.9m
2452343.59	2.7	OSN	0.9m	2452382.34	5.3	OSN	0.9m
2452344.74	4.6	APT	0.75m	2452385.34	5.5	OSN	0.9m
2452345.74	5.4	APT	0.75m	2452386.34	5.3	OSN	0.9m
2452346.36	4.7	SAAO	0.5m	2452387.39	4.2	OSN	0.9m
2452346.73	5.7	APT	0.75m	2452392.35	5.0	OSN	0.9m
2452347.40	5.0	SAAO	0.5m	2452394.35	4.3	OSN	0.9m
2452347.73	0.8	APT	0.75m	2452395.34	4.9	OSN	0.9m
2452348.36	6.0	SAAO	0.5m	2452396.36	3.5	OSN	0.9m
2452348.73	5.6	APT	0.75m	2452397.65	5.6	SPM	1.5m
2452349.34	6.3	SAAO	0.5m	2452398.47	2.3	OSN	0.9m
2452349.84	1.4	APT	0.75m	2452398.67	4.0	SPM	1.5m
2452350.38	5.3	SAAO	0.5m	2452399.36	3.9	OSN	0.9m
2452351.72	5.8	APT	0.75m	2452399.66	5.1	SPM	1.5m
2452352.36	5.3	SAAO	0.5m	2452400.67	5.1	SPM	1.5m
2452353.42	6.4	OSN	0.9m	2452402.66	5.3	SPM	1.5m
2452353.71	5.8	APT	0.75m	2452403.66	1.4	SPM	1.5m
2452354.42	6.4	OSN	0.9m	2452404.72	2.6	SPM	1.5m
2452354.72	3.6	APT	0.75m				

and multiple-frequency techniques (programs PERIOD, Breger 1990; PERIOD98, Sperl 1998), which utilize Fourier as well as multiple-least-squares algorithms. The latter technique fits a number of simultaneous sinusoidal variations in the magnitude domain and does not rely on prewhitening.

To decrease the noise in the power spectra, we combined the  $y$  (4393 new measurements) and  $v$  data (4147

new measurements). The dependence of the pulsation amplitude on wavelength was compensated by multiplying the  $v$  data set by an experimentally determined factor of 0.70 and increasing the weight of these data points by 1/0.70. This scaling creates similar amplitudes but does not falsify the power spectra. Note that different colors and data sets were only combined to detect new frequency peaks in the Fourier power spectrum and to determine the

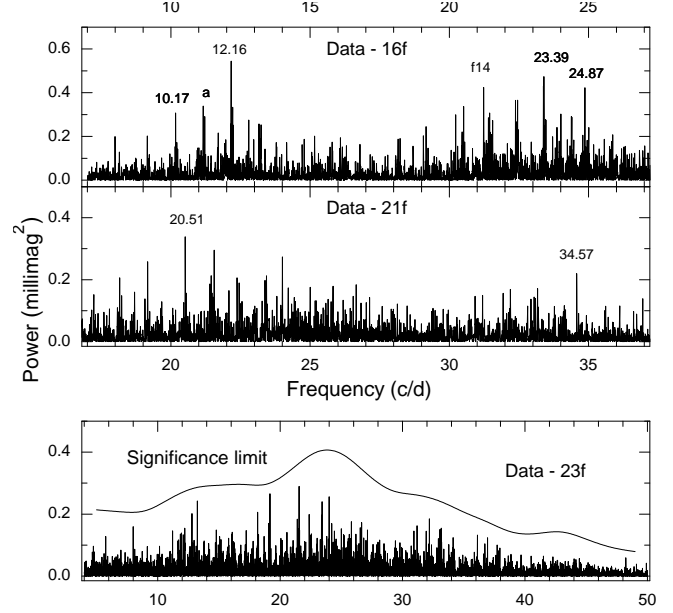


**Fig. 2.** Power Spectra of FG Vir for the 2002 photometry. The numbering scheme (e.g.,  $f_1$ ) of the peaks refer to the frequencies found in the 1992–1996 data (Breger et al. 1998). Some 1 c/d alias peaks have been marked by ‘a’ for clarity. This figure shows that the 16 pulsation modes with the highest amplitudes were also present a decade earlier. Top: The dominant mode and the spectral window. Other panels: Power spectra in the main pulsation region after prewhitening 1, 8, and 11-frequency solutions.

significance of the detection. The effects of imperfect amplitude scaling and small phase shifts between colors can be shown to be very small. For prewhitening, separate solutions were obtained for each color by multiple least-square fits (PERIOD98).

No special weighting of the data points according to their accuracy was applied, except for assigning a weight of 0.25 to 3 nights of the SAAO 75-cm telescope measurements (dates 245 2327 to 245 2336) and the 5 last OSN nights (JD 245 2387 to 245 2396). The measurements were of slightly lower precision (see previous section).

In the analysis of the Delta Scuti Network campaign data, we usually apply a specific statistical criterion for judging the reality of a newly discovered peak in the Fourier spectra, viz., a ratio of amplitude signal/noise = 4.0 (see Breger et al. 1993). For FG Vir, previous campaigns have led to the discovery of 24 significant and 8 probable frequencies. In order to examine the long-term stability of the pulsation of FG Vir we carried out an independent analysis of the new data to see which of the



**Fig. 3.** Additional pulsation modes detected in the 2002 data after prewhitening 16 previously known frequencies. The values (in c/d) of the new modes are shown. Otherwise the symbols have the same meaning as in Fig. 2.

previously known pulsation modes could be detected in the new data.

Our analysis involves a number of different steps to be repeated. Each step involves the computation of a Fourier analysis (power spectrum) from the original data or a previously prewhitened fit. The dominant peaks in the power spectrum were then examined for statistical significance and possible effects of daily and annual aliasing. For computing new multifrequency solutions, the amplitudes and phases were computed separately for each color, so that even these small errors associated with combining different colors were avoided. Note that the new multifrequency solutions always were computed from the observed (not the prewhitened) data. Because of the day-time and observing-season (annual) gaps, different alias possibilities were tried out and the fit with the lowest residuals selected. The resulting optimum multifrequency solutions were then prewhitened and the analysis repeated while adding more and more frequencies, until the new peaks were no longer statistically significant.

Figures 2 and 3 show the results of the frequency search. No statistically significant peaks were found in the low-frequency region, which are therefore not shown in the figures. The question arises whether the adopted reduction procedures could have cancelled low-frequency terms intrinsic to the star. The data from the different telescopes were merged by adopting an artificial zero-point for each telescope: for the initial analysis the average magnitude was computed for each telescope and for later analyses the zero-point of the multifrequency solution was adjusted. This approach can, in principle, suppress real

low-frequency power, especially near 1.00 c/d. However, our data were gathered essentially with only four telescopes so that each data set contains enough measurements to detect low frequencies. Numerical simulations have shown that our reduction procedure should not have negatively influenced the low-frequency analyses. This potential problem also shows that multisite campaigns with large amounts of data gathered from few sites are more accurate than a collection from a large number of different telescopes.

Altogether 23 statistically significant peaks in the range of 9.2 to 34.6 c/d were found in the 2002 data. 17 of these were previously known. Of the six new frequencies, one peak is a combination frequency: the 24.87 c/d peak can be identified with  $f_1 + f_6$ , which are the modes with the highest photometric amplitudes. Two of the new modes are the secondary components of mode doublets (see next section).

The results of the search for multiple frequencies in the 2002 FG Vir data are shown in Table 2. Since the third decimal place of the frequencies is uncertain, only two decimal places are given. Exceptions are the close pairs.

We also list the seven previously announced frequencies not found to be significant in the 2002 data. Some may be present in the data, but do not reach the signal/noise criterion for a secure detection. In order to estimate their amplitude, we have reduced the noise by combining the two filters,  $v$  and  $y$  after scaling the  $v$  data by 0.70 in order compare with  $y$ . We have computed their amplitudes in an additional multifrequency solution including these frequencies and listed in the amplitudes in brackets. We note that  $f_{24}$  is not present in the data.

The power spectrum of the residuals (after subtracting a 23-frequency fit) contains additional information too. If all the pulsation modes on the star were found by us, the noise figure should show a steady, slow decrease with frequency. This is not seen. Inspection of the power spectrum indicates that many additional pulsation modes *in the same frequency bands as the detected modes* are present. These are the 11-13, 19-25 and 30-35 c/d regions. The significance limit adopted by us (4 x average amplitude of the noise sampled over 4 c/d regions) measures both observational errors and undetected peaks. Our previous applications of this limit to multisite data suggests that it is quite conservative and avoids incorrect frequency detections. The latter is important since stellar pulsation models attempt to fit every detection, so that incorrect frequencies are more harmful than undetected additional modes.

We conclude that while the present campaign has detected six additional modes, more modes are present in the star with amplitudes of 0.5 mmag or lower.

#### 4. Close frequency doublets and amplitude variability

It was shown by Breger & Bischof (2002) that the majority of the well-studied  $\delta$  Scuti stars show close frequency

**Table 2.** Amplitudes of the multiple frequencies of FG Vir

	Frequency <sup>1</sup> c/d	Amplitudes (2002)		Comments
		$v$ mmag	$y$ mmag	
$f_1$	12.72	32.3	22.1	
$f_2$	24.23	5.7	4.2	
$f_3$	23.403	5.9	4.3	doublet
new	23.397	1.3	0.8	doublet
$f_4$	21.05	4.5	3.1	
$f_5$	19.87	3.0	2.1	
$f_6$	12.154	6.1	4.2	doublet
new	12.162	1.3	1.0	doublet
$f_7$	9.66	5.3	3.7	
$f_8$	9.20	3.8	2.8	
$f_9$	19.23	2.5	1.6	
$f_{10}$	20.29	1.8	1.1	
$f_{11}$	24.19	2.3	1.7	
$f_{12}$	16.07	1.6	1.3	
$f_{13}$	34.12	0.7	0.6	
$f_{14}$	21.23	1.0	0.6	
$f_{15}$	11.10	0.8	0.7	
$f_{16}$	25.43	1.3	0.9	$= 2f_1$
$f_{21}$	24.35	1.1	0.9	
new	10.17	0.8	0.5	
new	24.87	0.8	0.4	$= f_1 + f_6$
new	20.51	0.6	0.7	
new	34.57	0.6	0.4	
Residuals		$\pm 4.1$	$\pm 3.7$	
Previous frequencies not found to be significant <sup>2</sup>				
$f_{17}$	33.06		(0.3)	
$f_{18}$	21.55		(0.4)	
$f_{19}$	28.14		(0.4)	
$f_{20}$	11.20		(0.4)	
$f_{22}$	11.87		(0.3)	
$f_{23}$	22.37		(0.4)	$= f_1 + f_7$
$f_{24}$	10.69		(0.1)	$= f_1 - f_3$

<sup>1</sup> The 'old' frequency notation from Breger et al. (1998) was used.

<sup>2</sup> Frequencies not found to be significant may be excited with small amplitudes, but the existence of  $f_{24}$  is not confirmed. They were not used for the final solution and residuals.

pairs. With insufficient frequency resolution this would resemble amplitude variability of a single mode. A good example is offered by the 8.65 c/d mode(s) in BI CMi (same paper), where two long observing seasons independently established a close frequency pair separated by 0.02 c/d as the appropriate explanation.

For FG Vir, we already noted the stability of the pulsation modes between 1992–1995 and 2002. A few modes, however, show amplitude changes. Breger et al. (1998) already noted the strong amplitude variability of the 23.4 c/d peak from 1992 to 1995, although the annual coverage was too short to look for short-term changes within an observing season. However, the 98d coverage of the

2002 data allows the detection of amplitude and period (phase) changes within the single year for the 12.15 c/d and 23.4 c/d peaks. Two probable explanations are: (i) two modes with close frequencies beating with each other, and (ii) a single mode with variable frequency and amplitudes. This problem was already examined in our analysis of BI CMi (Breger & Bischof 2002), where for a number of modes it was possible to choose between the two interpretations on the basis of a specific test in which the amplitude changes and associated phase changes of an assumed single mode were examined. This test works well when the amplitudes of the two close modes are similar. For BI CMi, the variable-amplitude single-frequency model could be rejected. For FG Vir, the phase test is not very helpful because of the very different amplitudes.

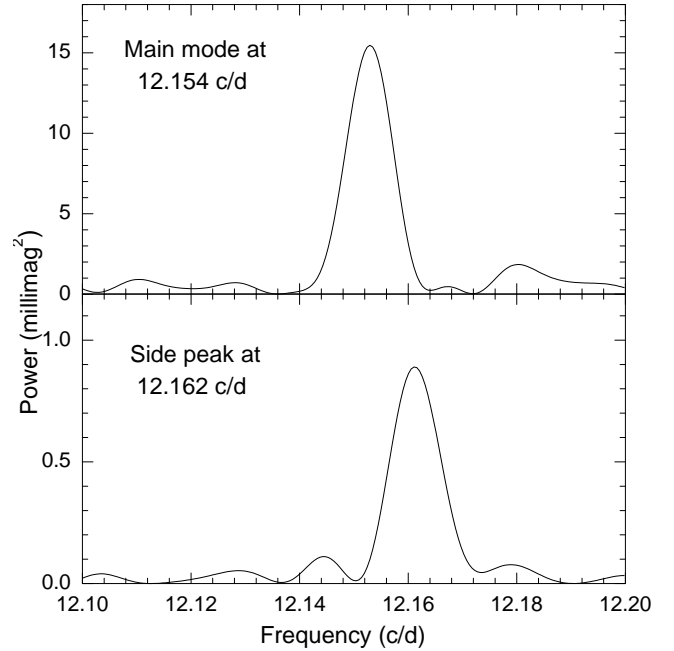
Let us examine the mode(s) near 12.15 c/d. The power spectra of the 2002 data are shown in Fig. 4. After the main mode at 12.154 c/d is prewhitened, we are left with a single peak at 12.162 c/d. Prewhitening both peaks leaves only noise. This provides strong evidence that two separate frequencies beating with each other are involved and that amplitude variability of a single mode is not responsible. However, the changes are at the limit or resolution for the 2002 data: the conclusion could be strengthened if a separate observing season would yield the same two peaks, thereby eliminating the possibility that the time coverage of the data conspired to suppress the additional peaks required by pure amplitude variability. We note that the two-frequency solution removes the observed amplitude and phase variability.

The main mode at 12.15 c/d has been shown to be radial on the basis of phase differences between the  $v$  and  $y$  light curves (Breger et al. 1999) and equivalent-width changes (Viskum et al. 1998). The secondary mode must, therefore, be nonradial because the period ratios of radial modes do not permit such close spacing. A nonradial mode with a frequency close to the frequency of the radial mode is one of the promising explanations for the observed amplitude variations associated with the Blazhko Effect in RR Lyrae stars (Kolenberg et al. 2003, Kovacs 2002). We speculate that the two phenomena in RR Lyrae and  $\delta$  Scuti stars may have a similar astrophysical origin.

The observational results for the 23.40 c/d modes are similar except that here a beat cycle of  $\sim 163$  d, instead of the 129 d for 12.15 c/d modes, is calculated. Again, this needs to be confirmed in data with even higher frequency resolution.

## 5. Discussion

16 out of the 17 frequencies found to be statistically significant in both the 1992–1995 and 2002 data are the modes with the largest photometric amplitudes. While this is hardly surprising, it also provides an argument in favor of the stability of the pulsation spectrum of FG Vir. In this regard the star differs from some other  $\delta$  Scuti stars such as 4 CVn (see Breger 2000), in which measurements taken ten years apart may even provide a first impression



**Fig. 4.** Power spectrum of the radial 12.15 c/d mode (see text for filter information). In the bottom panel the radial mode has been prewhitened. Note the different scales in power. This figure shows that the observed amplitude variability of the radial mode can be caused by the presence of a close nonradial mode.

of belonging to two different stars! Actually, in 4 CVn, the ‘disappeared’ modes have been shown to be still present, but with much smaller amplitudes.

The ‘missing’ modes in FG Vir all had  $V$  amplitudes between 0.4 and 0.8 mmag during 1995 with a statistical uncertainty of  $\pm 0.11$  mmag. The 2002 data show that most may still be present with the peaks at the correct frequencies, but with amplitudes less than 0.5 mmag. This is below the significance limit. We conclude that the differences can be explained by observational uncertainties in most cases.

*Acknowledgements.* This investigation has been supported by the Austrian Fonds zur Förderung der wissenschaftlichen Forschung, project number P14546-PHY. The Sierra Nevada observations were supported by the Junta de Andalucía and the DGI under project AYA2000-1580. PJA acknowledges financial support at the Instituto de Astrofísica de Andalucía-CSIC by an I3P contract (I3P-PC2001-1) funded by the European Social Fund. SMR also acknowledge the financial support by a Marie Curie Fellowship of the European Community programme ‘Improving the Human Potential’ under contract number HPMF-CT-2001-01146.

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